

Unintended consequences of sustainable architecture: Evaluating overheating risks in new dwellings

LINDA TOLEDO¹, PAUL C CROPPER¹ AND ANDREW J WRIGHT¹

¹ Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK

ABSTRACT: Governmental strategies to reduce heating demand from dwellings have led to a range of problems relating to ventilation and occupant comfort. In fact, growing evidence of uncomfortably warm homes has been appearing in UK consistently in the few last years. This paper discusses the overheating risk in four highly insulated homes in the UK where a mixed methods approach has been deployed to characterise areas of overheating risk, which have been found to occur with different degree of severity and different sources of risk, all related to design and occupant behaviour.

Keywords: thermal comfort, overheating, residential mixed-mode, field studies, Passivhaus, low carbon design

INTRODUCTION

Today's concern about climate change and its consequential humanitarian impact has led the UK government to develop strategies to reduce greenhouse gases emissions (Crown, 2008; HM Government, 2011). In an attempt to reduce energy consumption and associated carbon emissions from buildings, substantial changes have recently been made to UK building regulations, resulting in homes with significantly improved standards of thermal insulation and much higher levels of airtightness (DCLG, 2013).

However, growing evidence of uncomfortable (overheated) new energy efficient dwellings in the UK has appeared in the literature (DCLG, 2012; Dengel & Swainson, 2012; Taylor, 2014). This appears to be an unintended consequence of the UK CO₂ mitigation agenda (Davies & Oreszczyn, 2012) characterised by the dichotomy between highly efficient dwellings and summer thermal comfort.

Thermal modelling offers a powerful tool to predicting the possibility or probability of overheating and can be used to test the consequences of changes in specific parameters, such as orientation, house types, house layout, climate change, etc. under well-defined conditions. However, it has become clear that thermal modelling studies are not able reliably to model human behaviour and their thermal interaction with their environment (Beizaee, Lomas, & Firth, 2013) as these introduce unknown variants to parameters such as ventilation rate. Therefore, the design of energy efficient dwellings needs to be informed by knowledge gained from newly built highly insulated dwellings, leading to a built environment sustainable for people's needs and resilient to the changing climate.

Monitoring studies of dwellings with perceived overheating have often collected information about both

the use and the construction of the building (DCLG, 2012; Morgan, Foster, Sharpe, & Poston, 2015; Tabatabaei Sameni, Gaterell, Montazami, & Ahmed, 2015). This study is a contribution to that tradition, as it also investigates the design choices and consequences that govern the thermal strategy of highly insulated homes in the UK, by focusing, more specifically on current building regulation standards and Passivhaus-like buildings.

The study of energy efficiency and thermal comfort in highly insulated dwellings by its own nature stands between the spheres of building physics and social science. Accordingly, this paper presents initial results of a mixed methods research strategy that takes into account the transdisciplinary nature of the discipline of architecture, by integrating real world quantitative and qualitative data collected from building performance evaluation and interviews.

METHODS

The context of this paper is a larger study aimed at determining the likelihood of overheating in highly insulated dwellings in the UK, the sources of overheating risk, and the relations between overheating risk, on the one hand; and building design and occupant behaviour, on the other hand.

In order to achieve this objective, an in-depth study has been performed on four highly insulated British homes, where data has been collected by (a) conducting observational surveys on site, (b) recording environmental parameters and (c) submitting a number of questionnaires to the occupants. These are intended to evaluate the physical environmental measurements as well as the occupants' and design's role in the thermal performance of these homes.

The homes are of different types, which are presented in Table 1 and Table 2. None of the houses made use of any cooling devices such as fans or air conditioning units. It is worth noting that UK51 was the only refurbished (19th century) house, to a very high near-Passivhaus standard thermally.

Table 1: Overview of case studies homes with main construction characteristics.

| House code | House type n. bedrooms & location | U-value ext. walls (W/m2.K) | Thermal mass | Orien- tation |
|------------|---|-----------------------------------|-----------------|------------------|
| UK51 | Refurbished terrace 2 bedrooms Leicester (UK) | 0.12 | NO | E-W |
| UK52 | New detached bungalow 2 bedrooms Sandiacre (UK) | 0.09 | NO | N-S |
| UK54 | New terrace 3 bedrooms York (UK) | 0.19 | YES | N-S |
| UK55 | New detached 4 bedrooms York (UK) | 0.19 | YES | E-W |

Table 2: Overview of ventilation and solar control availability in the studied homes.

| House code | Ventilation type | Cross ventilation | Solar gain control |
|------------|---------------------|----------------------|-----------------------------------|
| UK51 | MVHR | YES | Internal blinds (partially) |
| UK52 | MVHR | YES | NO |
| UK54 | MV | YES | external overhangs (partially) |
| UK55 | MVHR | YES | external overhangs (partially) |

Longitudinal data were collected through HOBO loggers, which recorded environmental parameters, such as air temperature and Relative Humidity. Loggers were placed in every habitable room and the results have been analysed to map the most problematic areas or rooms in the house. In addition, the main bedroom temperatures were evaluated according to the CIBSE overheating threshold approach (CIBSE, 2013).

These longitudinal measurements were complemented by a number of occupant questionnaires for post-occupancy evaluation. Questionnaires were aimed at collecting a feedback on the effectiveness of new highly efficient designs, as well as collecting data

regarding occupants' behaviour, occupants' control, and occupants' thermal comfort sensation in order to capture how perceived thermal comfort and behaviour of the tenant relates to the environmental measurements in their home. The physical environmental monitoring was performed both by means of high-resolution intervals measurement and through spot measurements. The intervals measurement of air temperature (°C) and Relative Humidity were recorded every 10 minutes from 30 June 2015 till 13 August 2015. During this period a short heatwave occurred in England (from the 30 June 2015 till 2 July 2015), with temperatures exceeding 30°C on 1st July 2015.

Overall, the occupier questionnaires were administered in order to collect information about the house, its occupancy and the interactions between occupiers and the house: collection of background information about the house (microclimate, physical dimensions, occupants' background and household composition) was integrated with information about what the occupants think of their thermal environment and how the occupants adapt/interact with their thermal environment. The questionnaire included both ranking questions and qualitative open questions in order to determine if there were any problems with the design that is not accounted for by the 'forgiveness' factor (by forgiveness factor, it is meant the fact that "*occupants tolerate less than perfect conditions because they like the overall feel and design quality of a building*" (Nicholls, 2008, p.282).

RESULTS

Temperatures plots

Plotting the internal temperatures against the former CIBSE overheating criteria (2006) where a threshold of 26°C and 28°C is defined for bedrooms and living rooms respectively, made it evident that most of the high temperatures were located in the bedrooms on the upper floors. The living rooms performed better in terms of summer comfort. In fact, living rooms in houses UK51 and UK52 exceeded 28°C threshold only during the short heatwave experienced in the UK that summer.

More specifically, the temperature-related conditions of bedrooms and living rooms in the houses under review can be described in terms of (a) mean temperatures, (b) minimum temperatures and (c) maximum temperatures and temperature variation, as follows and as shown in figures 1, 2 and table 3:

(a) **Mean temperatures:** mean temperatures in the living rooms were lower than those of the bedrooms in all houses, mostly under 23°C. In the bedrooms, mean temperatures were up to 2°C higher. In house UK51, the mean temperatures recorded in the bedrooms were between 24°C and 25°C. In house UK52, the mean temperature recorded in the bedroom was just below

24°C. In house UK54, the mean temperature recorded in the bedroom was below 23°C. In house UK55, the mean temperature recorded in the bedroom was just below 25°C.

(b) Minimum temperatures: in house UK51 minimum temperatures in all the rooms considered were above 21°C at all times. In house UK52 the minimum temperatures recorded were lower (16-19°C). Minimum temperatures in house UK54 were just below 21°C, but, in sharp contrast with the other houses, temperatures have been maintained with no high peaks. Instead, in house UK55, the minimum temperatures of dining room and bedroom were below 17°C and above 21°C respectively. This reveals a different management of the temperatures within the house, since the dining room is located next to the kitchen and some extra heat gain could be expected to contribute to the temperatures.

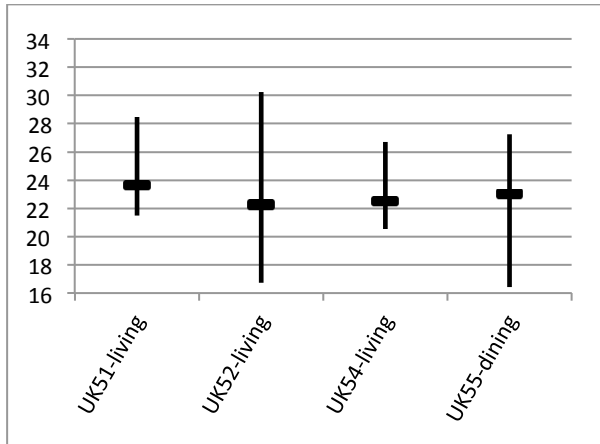


Figure 1: Max, min. and mean temperatures (°C) for living areas.

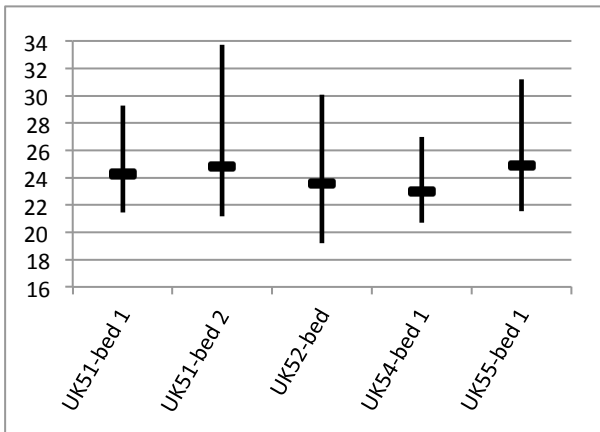


Figure 2: Max, min. and mean temperatures (°C) for bedrooms.

(c) Maximum temperatures and temperature variation: house UK51 recorded a max. of 29°C in the first bedroom and 33.7°C in the second bedroom. In the second bedroom the temperatures difference is 12.6

K, presumably due to natural ventilation. This was later confirmed by the occupants, who also claimed that they found this room uninhabitable during the heatwave. In house UK52, all occupied rooms showed a maximum of 30°C with temperatures showing a higher variation of 10/13°C. In house UK54, the mean temperature recorded was 22.5°C and 23°C in the living room and bedroom respectively. Noticeably, this house (UK54) presented the lowest maximum temperatures among all the case studies. Also, the rooms presented the smallest variation in temperatures of 6 K. In house UK55, the first floor bedroom recorded a maximum 31°C whereas the ground floor dining room recorded 27.3°C. In addition, it was noted that the temperatures recorded in the sunspace (winter garden) were extremely high, swinging from a min. 20°C to a max, 42°C. This could be attributed to the lack of both ventilation and solar control; and this can be confirmed by this sunspace's orientation (East), the lack of solar shading and by the occupant not opening the windows, resulting in heat gains then released in the adjacent rooms (see fig. 3).

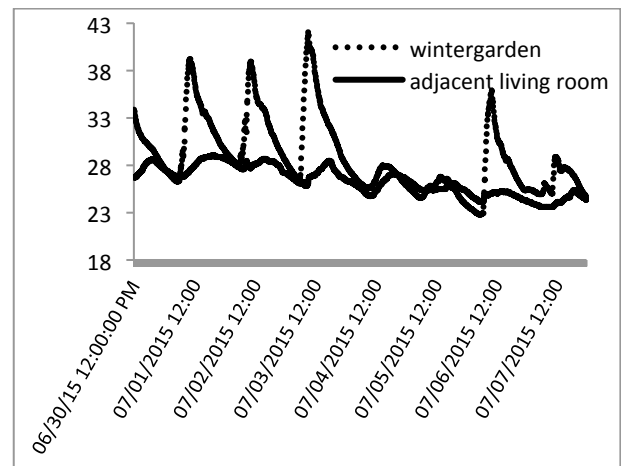


Figure 3: Recorded temperatures (°C) in the sunspace and adjacent living room from 30 June 2015 till 7 July 2015.

It is noticeable the fact that whilst UK52 and UK54 have almost similar average temperatures, they have at the same time a remarkable difference in temperature variation and maximum temperatures. These two houses were designed to optimize the use of natural ventilation through the windows; however house UK52 has a much higher level of insulation and it has no thermal mass exposed.

Table 3: Max, min., average and range temperatures.

| | Temp °C min | Temp °C max | Temp °C mean | Temp K range |
|-------------|----------------|----------------|-----------------|-----------------|
| UK51-bed 1 | 21.5 | 29.3 | 24.3 | 7.8 |
| UK51-bed 2 | 21.2 | 33.7 | 24.8 | 12.6 |
| UK51-living | 21.5 | 28.5 | 23.7 | 7.0 |
| UK52-bed 1 | 19.2 | 30.1 | 23.6 | 10.9 |

| | | | | |
|-------------|------|------|------|------|
| UK52-living | 16.7 | 30.3 | 22.3 | 13.5 |
| UK54-bed 1 | 20.7 | 27.0 | 23.0 | 6.2 |
| UK54-living | 20.6 | 26.7 | 22.5 | 6.1 |
| UK55-bed 1 | 21.6 | 31.2 | 24.9 | 9.6 |
| UK55-dining | 16.4 | 27.3 | 23.0 | 10.8 |

Frequency distribution and histograms

The former CIBSE Guide A (CIBSE, 2006) provides guidance for indoor temperatures for buildings including summer indoor comfort temperatures. The risk of overheating is calculated by thermal performance of buildings, measured against both a benchmark temperature and an overheating criterion. The general indoor comfortable operative temperature for bedrooms as listed in CIBSE Guide A is 23°C and the threshold operative temperature is 26°C. This overheating criteria establishes that if the mentioned threshold temperature (26°C) exceeds 1% of the occupied hours, the building suffers from overheating (CIBSE, 2006). It is worth mentioning that this criterion is been revised to embed the adaptive approach (CIBSE, 2015).

Looking at the frequency distributions (figure 4), and although in different intensity, all bedrooms exceeded the 26°C threshold. House UK51 and UK55 showed the most severe cases of high internal temperatures. In fact, when comparing the internal temperatures amongst a threshold of 26°C, it was found that house UK55 presented the worst performance with a 23% of monitored hours were above the 26°C threshold. This was followed by house UK51, where bedrooms 1 and 2 showed respectively an 8% and 15% percent of monitored hour above threshold. House UK52, showed a 10% over threshold hours. Finally the best performing house in terms of overheating was house UK54, where the threshold was exceeded for only the 2% of monitored hours.

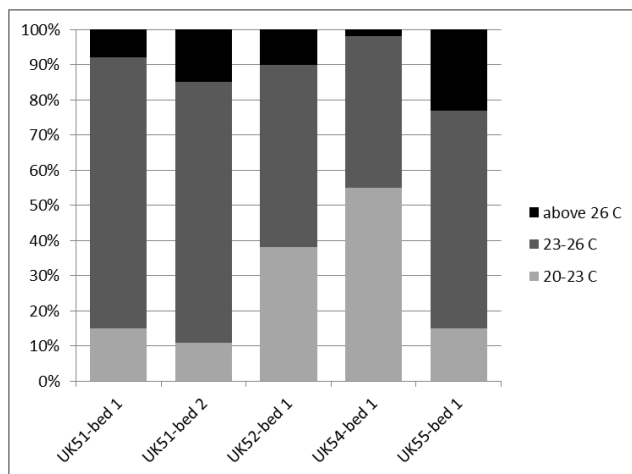


Figure 4: Stacked bar charts of temperature ranges of bedrooms.

Questionnaires

Occupants responded to two identical questionnaires, one submitted at the beginning of the study and one at the end of it. The goal of this strategy (double questionnaire) was that of seeking confirmation of the occupants' opinions and behaviours throughout different seasons. The first questionnaire was submitted in late spring/early summer 2015 and the second in mid-summer 2015.

When asked *how often the windows were kept open in order to cool a room*, occupants from houses UK51, UK54 said that they left the windows open to cool the house day and night. By contrast, the occupant of house UK52 left the windows open during daytime only, due to security concerns. Lastly, no cooling through windows opening was used in house UK55. These behaviours seemed confirmed by the temperature readings of most houses; the only exception is house UK51, where opening the windows seems to be insufficient to properly cool the house. These opinions were mostly maintained in both the first and second questionnaires.

When asked *how difficult is it to keep comfortably cool*, the responses from early till late summer (i.e. after the heatwave) showed that the occupants of house UK51 have difficulties in keeping cool the second bedroom (under the roof). For this reason, the occupants of this house slept in the cooler living room during the heatwave. The occupant of house UK52 claimed that she did not have a similar difficulty, in early summer. However by mid-summer the occupant did find it difficult to sleep due to excess heat and opted to go to the living room to open a window and - concern of burglary- keep herself awake by reading a book. The occupants of house UK54 said that they had difficulty to keep cool only in the small office, where windows were not opened due to building works nearby. Finally, the occupants of house UK55 stated that they experienced no difficulty in maintaining room temperatures comfortably cool in the first questionnaire; however in the second questionnaire the same occupants claimed that they had difficulties on keeping comfortably cool temperatures throughout the whole house and during all day, to the point that they felt the necessity to go outside in order to feel thermal relief.

DISCUSSION

Looking at the bar charts and the hours "above 26°C" (CIBSE overheating threshold), one can notice that the worst performing bedroom (in UK55) and the best performing bedroom (in UK54) are located in the same development and have the same materials and building specifications. The difference in those cases may partly be explained by the different designs and orientation, different ventilation system and ventilation management. In fact, whereas house UK55 delegates the provision of thermal comfort to the MVHR system, the

occupiers of house UK54 managed ventilation manually, thus allowing to keep the heat out during the day and to ventilate during the night. In a similar vein the two houses that rely most in natural ventilation had a reduced number of hours above the 26 °C threshold in this group. By contrast, the houses that manage ventilation through MVHR presented the highest number of hours above the 26°C threshold in this range and, consequently, they may be considered to have more chances to overheat.

Another noticeable finding that has emerged from this work is the distribution of hours in the range “between 23°C and 26 °C”. This temperature range can be seen as at high risk of overheating, since temperatures can quickly increase above the threshold. This is due to the very nature of highly insulated homes, where internal temperatures are responding rapidly to heat gains. In this respect, houses UK52 and UK54 showed the fewest hours between 23°C and 26 °C: 52% and 43% respectively. By contrast, house UK51 showed 77% and 74% of hours between 23°C and 26°C in bedrooms 1 and 2 respectively.

When considering the mean, minimum and maximum temperatures, house UK51 and UK52 have been found by their occupants to be too warm in the bedroom (often up to the point that the occupants had to move to another room in order for them to sleep well). The mean temperatures in those bedrooms were above 23°C. For this reason, one might consider that the CIBSE general indoor comfortable operative temperature for bedrooms, as listed in CIBSE Guide A (2006) of 23°C might need careful consideration when designing or assessing comfort and well-being in highly insulated dwellings. As far as the maximum temperatures are concerned, house UK51 recorded the highest temperatures in the bedrooms. After surveying this house (UK51) and taking into account the responses from the occupants, it can be hypothesised that the design of the house (open stack) may well have led to higher temperatures due to the exacerbation of temperature increase, typical of highly insulated dwellings and further contribution of the open stack in the top floor bedroom, as represented in figure 5.

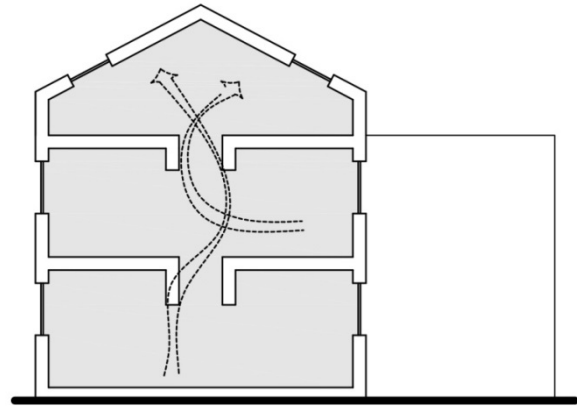


Figure 5: Representation of the stack effect through the stairwell in house UK51.

Another interesting design-related risk choice is provided by UK55. In this case the highest temperatures were recorded in the sunspace/winter garden (see fig. 6). This incorporated sunspace (winter garden) is an architectural feature acting effectively as a greenhouse incorporated to the building volume and acting as heat collector. However inappropriate use can lead to unwanted heat gains into the main house and higher temperatures, contributing further to overheating (in this specific case study, a temperature of up to 42°C was registered in the living room), see fig. 3.

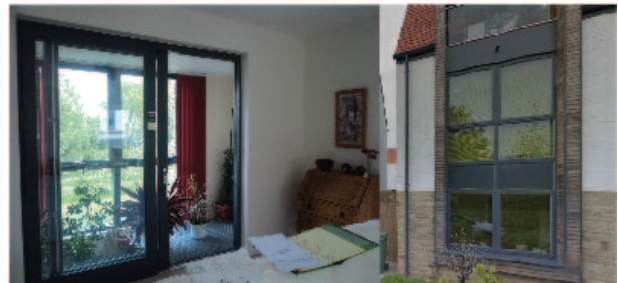


Figure 6: images of sunspace (winter garden) in house UK55.

Other monitored studies have shown that overheating occurs in similarly conceived homes in England, Wales and Scotland, where also predictive tools deployed have failed to identify overheating risks, and where also occupant behaviour has a high influence of uncomfortably high temperatures. Similarly, these studies also report that there is a lack of external solar shading which is contributing to unnecessary heat gains (Morgan et al., 2015; Ridley, Bere, Clarke, Schwartz, & Farr, 2014; Tabatabaei Sameni et al., 2015).

CONCLUSION

In general terms, it seems evident that the current ‘new’ way of designing homes in UK has perhaps not matured yet an understanding of how to innovate architecture in consideration of a -much needed- low

carbon design. In fact, this study has provided evidence that uncomfortable temperatures were found in all the houses under review. However, this has occurred with different degree of severity and apparently for a variety of reasons.

One of the factors that most impact on overheating experiences appears to be the presence or absence of natural ventilation. In fact, this study showed that in the houses where natural ventilation is applied consistently temperatures were reduced.

Also the study showed that the lack of solar control in general leads to excessive heat gains and quick response in temperature increase. This suggests that passive devices, such the sunspace (winter garden), should be considered a double-edged sword: if improperly used or unmanaged, in highly insulated buildings they may contribute an interesting space and useful source of heat outside warm periods, but also exacerbate overheating if improperly used.

The knowledge gained from these monitored case studies can be summarised in the following lessons learnt:

- Mechanical ventilation in dwellings is for fresh air, not for summer cooling; both occupants as well as designers need to understand this and the need to use additional natural ventilation in warm weather.
- Solar gains can cause severe overheating in highly insulated homes even in the UK, where shading has historically rarely been needed or used. Appropriate window design and shading is therefore required.
- There is a need for greater use of detailed simulation at the design stage, particularly regarding solar gains and ventilation, could be employed to improve designs; simpler tools may not inadequate for this sort of design, particularly in the case of less experienced designers.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the sponsorship of the Global Innovation Initiative (GII) project (2014-2016) "Reducing global energy use in buildings while improving occupant comfort and well-being: reversing the growing trend toward energy-intensive air-conditioning", funded by the British Council as part of an international partnership between BERG-Loughborough University (UK), CBE-UC Berkeley (USA), CARBSE-CEPT University (India), IESD-De Montfort University (UK). Also, authors would like to express their gratitude to Dr Lynda Webb for her useful comments on an earlier draft of this paper.

In addition, the authors would like to express their most sincere gratitude to the very patient and helpful volunteers of the houses surveyed.

REFERENCES

1. Beizaee, A., Lomas, K. J., & Firth, S. K. (2013). National survey of summertime temperatures and overheating risk in English homes. *Building and Environment*, 65, 1–17.
2. CIBSE. (2006). Guide A: Environmental Design. London: Chartered Institution of Building Services Engineers.
3. CIBSE. (2013). The limits of thermal comfort: avoiding overheating in European buildings. London: Chartered Institution of Building Services Engineers.
4. CIBSE. (2015). Guide A: Environmental Design. London: Chartered Institution of Building Services Engineers. <http://doi.org/10.1016/B978-0-240-81224-3.00016-9>
5. Crown. Climate Change Act 2008 (2008). UK: The Stationery Office Limited. Retrieved from http://www.legislation.gov.uk/ukpga/2008/27/pdfs/ukpga_20080027_en.pdf
6. Davies, M., & Oreszczyn, T. (2012). The unintended consequences of decarbonising the built environment: A UK case study. *Energy and Buildings*, 46, 80–85. <http://doi.org/10.1016/j.enbuild.2011.10.043>
7. DCLG. (2012). *Investigation into Overheating in Homes*. London: Crown Copyright. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7604/2185850.pdf
8. DCLG. The Building Regulations 2010. Conservation of fuel and power L1A. Conservation of fuel and power in new dwellings 2013 Edition (2013). NBS.
9. Dengel, A., & Swainson, M. (2012). *Overheating in new homes. A review of the evidence* (No. NF46). Milton Keynes: NHBC Foundation.
10. HM Government. (2011). *The Carbon Plan: Delivering our low carbon future*. London: Crown Copyright. Retrieved from http://www.decc.gov.uk/en/content/cms/tackling/carbon_plan/carbon_plan.aspx#
11. Morgan, C., Foster, J., Sharpe, T., & Poston, A. (2015). Overheating in Scotland: Lessons From 26 Monitored Low Energy Homes. *CISBAT 2015 International Conference "Future Buildings and Districts - Sustainability from Nano to Urban Scale"*, 167–172. Retrieved from <http://radar.gsa.ac.uk/3719/>
12. Nicholls, R. (2008). *The Green Building Bible: The Low Energy Design Technical Reference*. Green Building Press. Retrieved from <http://books.google.co.uk/books?id=0Lv-oAEACAAJ>
13. Ridley, I., Bere, J., Clarke, A., Schwartz, Y., & Farr, A. (2014). The side by side in use monitored performance of two passive and low carbon Welsh houses. *Energy and Buildings*, 82, 13–26. <http://doi.org/10.1016/j.enbuild.2014.06.038>
14. Tabatabaei Sameni, S. M., Gaterell, M., Montazami, A., & Ahmed, A. (2015). Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment*, 92, 222–235. <http://doi.org/10.1016/j.buildenv.2015.03.030>
15. Taylor, M. (2014). *Preventing Overheating*. London: Good Homes Alliance. Retrieved from http://gha.pht.surefirehosting.co.uk/downloads/pages/REPORT_GHA_Preventing_Overheating_FINAL140217.pdf

